Research on Fuzzy Regulation Strategies in the Constant Air Volume Air Conditioning System

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Abstract: The energy consumption of the constant air volume (CAV) system largely depends on the regulation strategies. Although some air conditioning systems are equipped with automatic regulation devices, others lack effective regulation strategies. To avoid wasting energy and presenting simple regulation methods, fuzzy regulation strategies for CAV systems are studied in this research. A CAV system of an office building is modeled and simulated with the Designer's Simulation Toolkit (DeST). The operating parameters are calculated based on the instantaneous load obtained from simulation. The operation of the system is divided into five stages according to different conception of "cold" or "hot" in different seasons. The relationship between the outdoor air temperature and the fresh air volume, and the supply air temperature is presented in the form of fuzzy rules. Then the building is simulated under different load conditions and the operating parameters are obtained from fuzzy reasoning. Finally, the effect of fuzzy strategies on energy consumption is analyzed and compared with the effects of the operating parameters obtained from simulation. The results show that energy consumption using a fuzzy regulation strategy is close to the energy consumption of knowing the exact load of the building, while the fuzzy regulation strategy can largely simplify the regulation of the air conditioning system.

Key words: constant air volume; fresh air volume; supply air temperature; fuzzy; regulation strategy

1. INTRODUCTION

During the design stage of air conditioning system, the equipment and the operating parameters are determined according to the most disadvantage condition. As the variation of outdoor air parameters and indoor load, the operating parameters must change accordingly. Therefore, effective regulation strategies are important for avoid wasting energy. CAV system is one of the most popular air conditioning systems and some researches have been done on the regulation strategies of CAV system. Gong Yanfeng determined the relationship between supply air condition and fresh air condition by analyzing the whole year air condition load. In their research the outdoor air conditions which have the same air treating course were divided into one region and the same operating strategy was adopted[1]. Wang Li analyzed the temperature control principles to achieve economical operation in CAV system, and presented improved control strategy to integrate fresh air control with indoor air temperature control [2].

Although many researches have been done on regulation strategy, most have given instructive conclusions, which are very abstract to both control system designers and operating persons. So it is necessary to present more straight regulation strategy through analyzing the operation of air conditioning system.

2. BUILDING AND AIR CONDITIONING SYSTEM FOR SIMULATION

In this research an office building in Harbin is selected for simulation. It is 45 meters long, 30 meters wide and 25.2 meters high. It has 7 floors and the typical floor area is 1350 square meters. Figure 1 is the typical floor plan.

The main building unit parameters are listed as follow. External wall comprises 20 millimeters cement mortar, 490 millimeters mortar clay and 20 millimeters lime mortar. And its thermal transmission coefficient is 1.241W/$m^{2\cdot}$K. Internal wall comprises 20 millimeters cement mortar, 240 millimeters mortar clay and 20 millimeters cement mortar, and its thermal transmission coefficient is 1.761W/$m^{2\cdot}$K. The roof adopts air-entrained concrete heat preservation structure. It comprises 20 millimeters cement mortar, 200 millimeters perforated concrete and 130 millimeters ferroconcrete. Its thermal transmission coefficient is 0.812W/$m^{2\cdot}$K. The floor adopts ferroconcrete floor. It comprises 20 millimeters cement mortar, 80 millimeters ferroconcrete and 20 millimeters cement mortar, and its thermal resistance is 0.098 $m^{2\cdot}$K/W. Internal door adopts single wood door, and external door is double wood door. The window adopts double aluminum alloy windows.

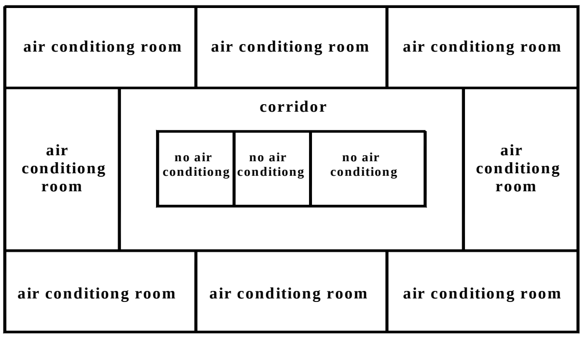

Fig.1 Typical floor plan of the simulation building

Indoor air design conditions is set as follow: dry bulb temperature is 26℃ and relative humidity is 50% for summer; dry bulb temperature is 20℃ and relative humidity is 50% for winter. Density of person stream is 5m^2/person. Load of person includes sensible heat load and latent heat load. Sensible heat dissipating capacity of person in office building is set 61W; the latent heat dissipating capacity is 73W; and moisture dispersed amount is 109g/h[3]. Lighting load is 20 W/m^2 and equipment load is 20 W/m^2. The minimum fresh air volume for per person is 30m^3/h. The air conditioning system is intermittent operation, its operation time is from 7:00 to 18:00 and no off day is considered during the simulation.

The air conditioning system of typical floor is CAV system with primary return air. The air-conditioning unit include: preheating section, mixing box section, cooling coil section, humidifier section, air reheater and air fan. The design supply air volume is 7.72kg/s, and minimum fresh air volume is 2.08kg/s. Design supply air temperature is 13.5^{o}C and air moisture is 9.68kg/kg dry air for summer; supply air temperature is 8.1^{o}C and air moisture is 6.45kg/kg dry air parameter for winter. The fresh air volume is controlled based on outdoor air enthalpy and it is supposed that all fresh air can be used in transition period. Only air condition demand of exterior room is considered.

3. EXTRACT OF FUZZY OPERATING STRATEGY

3.1 Determination of Range for Extracting Fuzzy Rules

Harbin lies in cold area, and the difference of outdoor air temperature between summer and winter is very large. So it is inappropriate to divide the entire range of outdoor air temperature as a whole. It is well known that people will have different feeling of high temperature or low temperature in different season. Therefore, the operating time of air conditioning system is divided into 5 stages with consideration of outdoor air temperature and indoor air set parameters. Three stages accord with winter indoor set parameters and two accord to summer indoor set parameters. The stages are set as follow.

Stage one includes January and February. The range of outdoor air temperature is from -35^{o}C to -0.6^{o}C and the total operating time of air conditioning system is 649 hours.

Stage two includes November, December and a few days of October. The range of outdoor air temperature is from -29^{o}C to 5^{o}C and the total operating time of air conditioning system is 704 hours.

Stage three includes March and 22 days of April. The range of outdoor air temperature is from -17^{o}C to 23^{o}C and the total operating time of air conditioning system is 583 hours.

Stage four includes May, a few days of April, September and October. The range of outdoor air temperature is from -3^{o}C to 32^{o}C and the total operating time of air conditioning system is 1067 hours.

Stage five includes June, July and August. The range of outdoor air temperature is from 11°C to 33°C and the total operating time of air conditioning system is 1012 hours.

3.2 Fuzzy Division of Outdoor Air Temperature

According to the division of operating time, the domain of temperature is divided into seven fuzzy sets[4]. The seven sets are negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM) and positive big (PB). Their fuzzy language value are very low, a little low, low, appropriate, high, a little high and very high respectively. And triangular membership function is used in this research as shown in Figure 2.

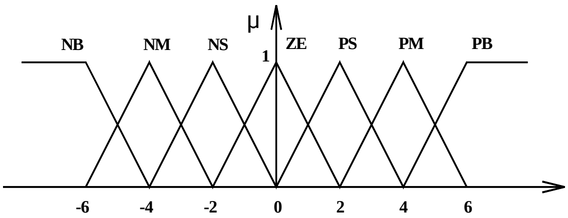

Fig.2 Triangular membership function

3.3 Fuzzy Division of Fresh Air Volume

The range of fresh air volume is from 2.08kg/s to 7.72kg/s. According to the variation of outdoor air temperature and indoor air set point, the fresh air volume can reach the minimum and the maximum volume in every stage. So the range of fresh air volume can be divided directly and it is divided into seven fuzzy sets, which are NB, NM, NS, ZE, PS, PM and PB.

3.4 Fuzzy Division of Supply Air Temperature

The office building is simulated by DEST and the supply air temperature can be calculated through follow formula:

$$t_o = t_N + Q_x / G \cdot c_p \qquad (1)$$

where: t_o——supply air temperature (°C)

t_N——indoor air temperature (°C)

Q_x——sensible load (W)

G——supply air volume (kg/s)

c_p——specific heat of air (KJ/kg·°C), 1.01KJ/kg· °C

According to the results of calculation, the supply air temperature varies a lot due to indoor air set point. So the domain of supply air temperature is divided according to different indoor air set point.

The supply air temperature varies from 9.77°C to 25.2°C corresponding to winter indoor air set point, while it varies from 17.9°C to 29°C for summer indoor air set point. These two domains are divided into 7 fuzzy grades respectively, which are NB, NM, NS, ZE, PS, PM and PB.

3.5 Extract of Fuzzy Strategies

Based on the data obtained from simulation, outdoor air temperature, supply air temperature and fresh air volume of each hour are included in one group, and then the fuzzy set and grade of membership of each parameter are determined. The ones which have the maximum membership are selected, so is its corresponding fuzzy set. For each group of data, the selected fuzzy sets and their grade of membership can obtain one rule. For example, if one group of data is (a, b) and their corresponding fuzzy sets are NB and NS, then this rule is: if a is NB then b is NS. The intensity of this rule is:

$$(R) = \max \mu(a) \times \max \mu(b) \qquad (2)$$

Tab.1 Fresh air volume fuzzy regulation strategy

Fuzzy scale of T_{out}	Fuzzy scale of fresh air volume				
	Stage one	Stage two	Stage three	Stage four	Stage five
NB	NB	NB	NB	NM	PB
NM	NB	NB	NM	NM	PB
NS	NB	NB	NM	NS	PB
ZE	NB	NB	NS	ZE	PB
PS	NB	NM	ZE	PS	NB
PM	NB	NM	PB	PM	NB
PB	NM	NS	PB	PB	NB

The incompatible rules are selected according to rule intensity, and those ones which have small intensity will be abandoned. Then the fuzzy rule base can be obtained.

Because outdoor air temperature of each stage is divided into seven fuzzy sets, at most seven rules can be obtained for each stage. Based on different stages, fuzzy rules between outdoor air temperature and supply air temperature, fresh air volume can be obtained. They are listed in table 1 and table 2.

Tab.2 Supply air temperature fuzzy regulation strategy

Fuzzy scale of T_{out}	Fuzzy scale of supply air temperature				
	Stage one	Stage two	Stage three	Stage four	Stage five
NB	PB	PS	ZE	PB	PS
NM	PM	ZE	NS	PM	ZE
NS	PS	ZE	NM	PS	NS
ZE	PS	NS	NB	ZE	NM
PS	ZE	NS	NB	NS	NB
PM	ZE	NM	NB	NM	NB
PB	NS	NB	NB	NM	NB

4. IMPACT OF FUZZY CONTROL STRATEGY ON SYSTEM OPERATION

The fuzzy regulation strategies obtained from treating of simulation data can reflect the heat characteristic of the simulation building to a certain extent. For an office building, only the indoor heat disturbance will change due to different working condition. In order to validate the impact of fuzzy regulation strategy on system operation, the structure of the office building is maintained and the indoor heat disturbances are reset.

4.1 Selection of Parameters for Validation

The density of person stream is changed to 6.5m^2/person and the equipment load is changed to 10 W/m^2, and other parameters are the same as original model of the building. Then the building is simulated and hourly load can be obtained.

On the basis of simulation result, the parameters of typical floor air conditioning system are calculated. The supply air volume is 6.26kg/s，and minimum fresh air volume is 1.60kg/s. Design supply air temperature is 13.5^{o}C and air moisture is 9.72kg/kg dry air for summer; supply air temperature is 8.2^{o}C and air moisture is 6.49kg/kg dry air for winter. Then the fresh air volume and the supply air temperature are calculated.

Functioning fuzzy subset method[5] is used for fuzzy reasoning in this research. And the center-of-gravity method is used for the defuzzification. On the basis of the division of different stages, the supply air temperature and fresh air volume can be obtained through fuzzy reasoning.

4.2 Impact on Energy Consumption of Air Conditioning System Operation

Since fuzzy control strategy of the air conditioning system is the primary object in this research, no actual equipment is considered and the energy consumption is calculated according to the change of air condition. The air is treated to dew point and then reheated to the supply air temperature. In view of outdoor air temperature is too low, preheating is adopted. Therefore the energy consumption includes three parts, and they are the energy used to preheat outdoor air in cold winter, energy consumption of the cooling coil and the air reheater. The energy consumption can be calculated by the following formula:

$$E=G_w(i_{w1}-i_w)+Gc_p(t_o-t_L)+G(i_c-i_L) \qquad (3)$$

where: i_o——enthalpy of supply air (kJ/kg);
i_c——enthalpy of apparatus dew point (kJ/kg);
i_w——enthalpy of outdoor air(kJ/kg);
i_{w1}——enthalpy of air for preheating(kJ/kg);
d_o——air moisture (kg/kg dry air);
t_L——dewpoint temperature (^{o}C);
G_w——fresh air volume(kg/s)；

The variation of fresh air volume can affect the load of fresh air directly and the change of supply air temperature will have influence on the energy consumption for reheating.

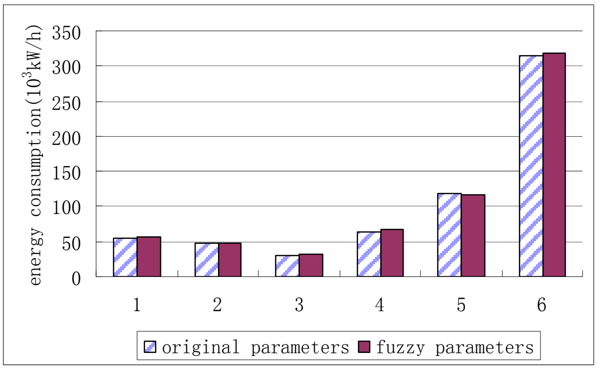

Fig.3 Comparison of energy consumption

In order to analyze the impact of fuzzy regulation strategy on energy consumption, the energy consumption is calculated using fuzzy parameters (parameter calculated based on fuzzy regulation strategy and fuzzy reasoning) and original parameters (parameters calculated from the exact load) respectively. And the results are shown in figure 3.

As is shown in the figure, the energy consumption of using fuzzy parameters is close to that of using original parameters. One reason is that some incompatible rule are selected or abandoned during rule extract. And it is also because that fuzzy reasoning can obtain some fixed value when the fuzzy regulation strategies are used. It is also can be seen in the figure that at stage one, stage four and stage six the energy consumption of fuzzy parameters is a little bigger than that of original parameters. However it is necessary to point out that the latter is obtained on the assumption that the exact load of the building is known, which usually can not be known in reality.

5. CONCLUSIONS

The outdoor air temperature is the main factor influenced the load of the air conditioning system. According to people's different conception of temperature "high" or "low" in different season, the fuzzy regulation strategy is presented in this research. The form of fuzzy regulation strategy is very simple and more fits the logic of people. It can avoid wasting of energy and can largely simplify the regulation of air conditioning system.

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